This document was prepared in conjunction with work accomplished under Contract No. AT(07-2)-1 with the U.S. Department of Energy.

Acc# 40079

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SAVANNAH RIVER LABORATORY

DPST-72-521

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October 19, 1972

M E M O R A N D U M

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PRESSURE FEEDBACK EFFECTS IN REACTOR TRANSIENTS

INTRODUCTION AND SUMMARY

The injection of steam into the reactor vessel from fuel or target assemblies during flow instability, or the formation of steam within the vessel from flashing, causes an increase in pressure within the hydraulic system. In the present version of AA1 computer code, the increase in pressure is calculated explicitly for each time step. However, the change in pressure is not fed back into the calculation where it may have a major effect on the calculated course of a transient. In most cases the feedback effect would be to dampen the power oscillations; however, it is possible to conceive of unlikely situations in which a transient could be aggravated. This memorandum presents an improved method to calculate reactor vessel pressure and methods to account for the pressure feedback effect for three significant phenomena: initiaton of excursive flow instability in assemblies, flashing of assembly coolant within the moderator space, and reduction of reactor coolant flow as a result of cavitation in the external hydraulic system. Information required for incorporation of these feedback effects into the AA1 computer code is provided in this memorandum.

DISCUSSION

General

Development of the pressure feedback determination was made using the COMBINE-AC code as documented in Ref. 1. Although this code does not contain all of the refinements found in the current AA1 code, it was used to develop the original external hydraulics models. The author's familiarity with the COMBINE-AC programming permitted a quicker task completion. The comparative effects of pressure feedback were made using typical Mark 14-30C input data prior to and after completion of the modifications to the code. The data are not for any specific reactor charge, but are realistic for generalized calculations.

Calculation of Pressure Feedback Effect on Flashing of Coolant

In the current model of AA1, it is assumed that assembly coolant in the temperature range between the saturation temperature at the bottom of reactor vessel and the temperature for initiation of excursive flow instability will flash to form steam in the lower region of the moderator space. The saturation temperature at the bottom of the tank (TLIM1) is an input variable, but is normally considered to be 120.0°C. This value is invariable throughout the course of the calculation, although realistically the saturation temperature would increase with steam formation.

For each calculational pass, the mass of steam formed during the interval of time under consideration is explicitly calculated based on a material and heat balance. This mass of steam; however, is stored for eventual use in the PEPTAL subroutine of AA1 to calculate pressures in the confinement system. The pressure within the reactor vessel is also calculated in the SFLSQR subroutine as incidental information and is printed as "smoothed" tabular data. Feedback of the pressure effects requires that the pressure be calculated and used at each time step rather than stored. The mass in pounds of steam formed during each time increment is currently calculated in the AKSDNT subroutine as SF(INCRE).

To incorporate pressure feedback into the flashing calculation, overpressure is determined at each time step by the following equation:

```
ØVERPR = 0.00305*(2.094*(SF(INCRE)*2.16/(SUBKUL*DELTAT))**1.5)**1.8
```

where:

ØVERPR = overpressure in psig

DELTAT = time interval for calculational step, sec.

SUBKUL = moderator subcooling at time of incremental calculation
= TLIM1 minus reactor effluent temperature, °C.

The equation is based on CMX steaming experiments[2,3] in which overpressures up to 7 psi were measured in the Crossflow Tank with bulk moderator subcooling as low as 12°C, and in the single lattice position tank in which overpressures up to 95 psi were measured. Derivation of this equation is presented in the Appendix. It is recognized that the equation for overpressure is the least accurately defined variable in this feedback analysis. Overpressure is dependent upon a number of variables which have not yet been quantitatively defined. It is further recognized that accuracy diminishes as operating conditions deviate from experimental conditions. At overpressures in excess of the reactor structural limitations (~13 to 30 psi depending upon the reactor and charge weight), the entire AAl transient calculation is tenuous. The experimental data [2,3] used in the derivation of the equation, however, were used in the STEAM code, which is the basis for the steam void coefficients of reactivity used in AAl.

During the initial determination of steady state conditions, the saturation pressure corresponding to TLIM1 should be calculated to establish a base pressure, PFLASH. If TLIM1 is less than 125.5°C, then

PFLASH = 473.68-TLIM1*(16.76-TLIM1*(0.22254-
TLIM1*(0.13112E-2-0.30231E-5*TLIM1)))

If TLIM1 is greater than 125.5, then:

PFLASH = -103.15+TLIM1*(2.7494-TLIM1*(0.26086E-1-0.10242E-3*TLIM1))

where:

PFLASH = saturation pressure corresponding to TLIM1, psia.

The absolute pressure at any time during the transient, PNØW, that corresponds to the temperature for flashing is:

PNØW = PFLASH + ØVERPR

Note that ØVERPR is initialized at 0.0 during the steady state determination. Overpressure may change for each time interval; however, the base pressure remains constant. TLIM1 is now recalculated at each interval as a function of PNØW as follows:

If PNØW is less than 33.5,

TLIM1 = 63.9013+PNØW*(3.3683-PNØW*(0.66181E-1-0.61415E-3*PNØW))

If PNØW is between 33.5 and 69.0,

TLIM1 = 80.7892+PNØW*(1.8016-PNØW*(0.16191E-1-0.68743E-4*PNØW))

Because of a dependence loop which occurs in the computer code (TLIM1 is dependent upon overpressure, which is dependent upon steam flow, which is dependent upon subcooling, which is dependent upon TLIM1), the value of TLIM1 used prior to the overpressure calculation must be converged with the TLIM1 value determined after the overpressure calculation. Otherwise a divergent oscillation in the calculated values occurs as the code steps through time. A convergence criteria on TLIM1 of 0.002°C is adequate.

Calculation of Pressure Feedback Effect on Initiation of Flow Instability

In the current model of AA1, it is assumed that excursive flow instability is initiated when the average coolant effluent temperature from an assembly equals the minimum saturation temperature within the assembly. Minimum saturation temperature is determined from an explicit calculation of minimum absolute saturation pressures (PSIA) within specific assembly types and as a function of total coolant flow through the reactor system. The effect of reduced flow as a result of cavitation is currently included in the calculation of PSIA in the ASSPRS subroutine. PSIA is transferred to the SATEMP subroutine where the critical effluent temperature for the initiation of flow instability, TLIMHI(I), is calculated. Because the pressures are additive, the steam surge effect can be incorporated by adding ØVERPR to PSIA at each time step for the computation.

Calculation of Pressure Feedback Effect on Cavitation Flow

The reduction in reactor flow that results from excessive reactor effluent temperature is calculated in the POLYFN subroutine. The flow temperature relationship is expressed as polynomial equations which were derived from measured reactor data extrapolated to zero flow for a saturation temperature corresponding to the static head (plus blanket gas pressure) at the location of cavitation. This is shown as the lowest curve on Figure 1 for P and K reactors. A different set of curves is applicable to C reactor; however, they are not presented in this memorandum because the necessary distinction between reactors is already programmed into AA1.

In the expanded calculation it is assumed that cavitation is solely a function of local saturation conditions; hence a change in pressure will alter the temperature for cavitation by an amount equal to the corresponding change in saturation temperature at the new pressure. This assumption is reasonable for small increases in pressure but may not be valid for large pressure changes. Because the calculation is based on pressure change rather than temperature change, the cavitation curve for zero overpressure was calculated in terms of pressure rather than temperature as shown by the lowest curve on Figure 2. A family of curves can then be constructed as a function of overpressure because the pressures are additive. Thus, for saturation conditions corresponding to 30 psia, flow would be about 36,000 gpm if there were no overpressure. If overpressure were 10 psi, flow would be about 119,000 gpm.

Because the curves are parallel, flow corresponding to 10 psi overpressure may be geometrically determined from the zero overpressure curve by subtracting the 10 psi from 30 psi. At 20 psia on the zero overpressure curve, the flow is also 119,000 gpm. Because the flow-overpressure relationship can be determined from a single curve in this manner, multiple polynomial expressions and interpolation are not necessary in the computer program.

In the calculational procedure, the reactor effluent temperature at the location of potential cavitation, TØUT(NWHEN), is examined for reasonableness with regard to being in the range where cavitation could occur regardless of pressure. If the reactor effluent temperature is less than 98.0°C, the entire cavitation calculation is bypassed and the cavitation flow is defined as being equal to flow with no cavitation.

```
IF(TØUT(NWHEN)·LT. 98.0) FLØP(NWHEN) = YUK
```

where:

FLOP(NWHEN) = reactor cavitation flow at time step NWHEN, gpm

YUK = reactor flow if cavitation does not occur, gpm.

If TØUT(NWHEN) is greater than 98.0, then the corresponding saturation pressure is calculated:

If TØUT(NWHEN) is less than 125.5, then:

```
PSATO= 473.68-TOUT(NWHEN)*(16.76-TØUT(NWHEN)*(0.22254-
       TØUT(NWHEN)*(0.13112E-2-0.30231E-5*TØUT(NWHEN))))
```

If TOUT(NWHEN) is greater than 125.5, then:

```
PSATO =-103.15+TØUT(NWHEN)*(2.7494-TOUT(NWHEN)*(0.26087E-1
       -0.10242E-3*TØUT(NWHEN)))
```

where:

PSATO = saturation pressure corresponding to TØUT(NWHEN), psia

Overpressure is then subtracted from PSATO to permit use of a single cavitation curve:

```
P = PSATO - ØVERPR
```

where:

P = saturation pressure geometrically adjusted for overpressure, psia.

This pressure, P, is then converted back to the corresponding saturation temperature. If the pressure is less then 33.5, then:

TSAT=63.9013+P*(3.3683-P * (0.66181E-1-0.61415E-3*P))

If pressure is greater than 33.5, then:

TSAT=80.7892+P*(1.8016-P*(0.16191E-1-0.68743E-4*P))

where:

TSAT = saturation temperature geometrically adjusted for over-pressure, °C

TSAT is now checked for reasonableness. If TSAT is less than 98.0, TSAT is set equal to 98.0 to prevent overranging the polynomial expressions for flow. Cavitation will not occur for any reasonable set of reactor operating conditions for TSAT=98.0. Cavitation flow is now calculated by the same set of polynomial expressions as currently used in the PØLYFN subroutine of AA1 except that TSAT replaces the variable T. In addition, statements are added for each reactor grouping such that if the calculated cavitation flow is greater than reactor flow without cavitation, then the cavitation flow is redefined as being equal to reactor flow without cavitation. Finally the term FLØW(NWHEN), which is the reactor flow in gpm to be used throughout the remainder of the time step, is set equal to FLØP(NWHEN), the cavitation flow. This statement was omitted from Ref. 1 and resulted in an abrupt recovery of normal flow rather than a gradual recovery as the effluent temperature decreased.

Flashing of Bulk Moderator

A fourth phenomenon in which pressure feedback could have a significant effect is that of flashing of moderator as it travels upward into regions of lower saturation temperature within the reactor vessel. No attempt was made to incorporate this into the calculation because the basic phenomenon itself is not currently calculated. It is recommended, however, that when this effect is taken into account that feedback of pressure be made an integral part of the model. Flashing of bulk moderator may be an important factor in reducing the consequences of a slow transient such as a gang withdrawal accident.

Comparison of Transients with and without Pressure Feedback

The effects of pressure feedback are illustrated in calculations of two gang withdrawal accidents using the same input data. The results are plotted on Figure 3. Initially, the relative power transient is identical. At 13.45 seconds after the start of the transient, coolant from the first histogram group begins to flash, at 15.00 seconds the second group flashes, and at 18.10 seconds the third group starts. By 22.10 seconds, tank pressure has increased 0.03 psi and the fourth group flashes. In both cases, sufficient steam has formed to override the rod driveout effects and relative power decreases from 1.28 in both cases to 1.16 without feedback and 1.18 with feedback. Flashing decreases and power again rises to 1.38 at 25.05 seconds without feedback and 24.95 seconds with feedback.

Flow instability in the first histogram group begins, and without feedback three groups are unstable by 25.50 seconds and cavitation begins. With feedback, only two groups reach instability because the critical effluent temperature has increased by 1.5°C. Cavitation is delayed until 26.20 seconds at which time reactor flow is reduced 4.0%. Flow is reduced 3.9% without feedback. The first significant difference in the cases become evident as a result of the different number of assemblies subjected to flow instability. The greater amount of steam results in a power reduction to a value of 0.68 relative to preaccident power which is sufficiently low to permit recovery of flow in the unstable fuel assemblies while the targets continue to adiabatically heat. With feedback, the minimum relative power is 0.86 and melting in six fuel assemblies begins at 30.15 seconds because power is not reduced sufficiently to permit recovery of flow. Power begins to decrease and the targets recover stable flow at 32.90 seconds. Relative power then continues to decrease to 0.25 at 50 seconds at which time the calculation was terminated. Full reactor flow recovery was achieved at 27.50 seconds in the case with feedback.

Without feedback, the lower power also permitted recovery of reactor flow. Flow recovery in the fuel, however, resulted in a second relative power peak of 1.46 at 33 seconds. This resulted in instability in the fourth and fifth groups and a subsequent reduction in reactor power. Melting of targets from the initial power surge began at about 35 seconds and a relative power surge to 3.2 was calculated. Severe cavitation reduced flow to zero and all histogram groups were either melting or adiabatically heating at the termination of the calculation.

This comparison shows that pressure feedback can be a significant factor in determining the course of an accident transient, and it is recommended that the models be incorporated into AA1 during the next general revision. It should be recognized that the example presented in this memorandum showed a significant damping effect; conceivable, but unlikely, cases can exist in which the transient would be aggravated by pressure feedback.

WSD:vpb

REFERENCES

1. W. S. Durant, S. D. Harris, and L. R. Jones, Engineering Development for the COMBINE Code, DPST-71-382, June 7, 1971. (Secret)

2. D. A. Ward, "Transient Steaming Experiments," DPST-59-13-1, January 1959. (Secret)

3. D. A. Ward, "Pressure Transients in a Reactor Tank Caused by Boiling in Fuel Assemblies, Progress Report No. 2", DPST-60-476. (Secret)

4. W. S. Durant, "Calculated Pressure Rise from Pump Shaft Break Accident for Mark VB and VIB Charges," DPST-63-345, Feb. 5, 1964. (Secret)

FIGURE 1

REACTOR CAVITATION CURVES IN TERMS OF SATURATION TEMPERATURE
(P-K Reactors)

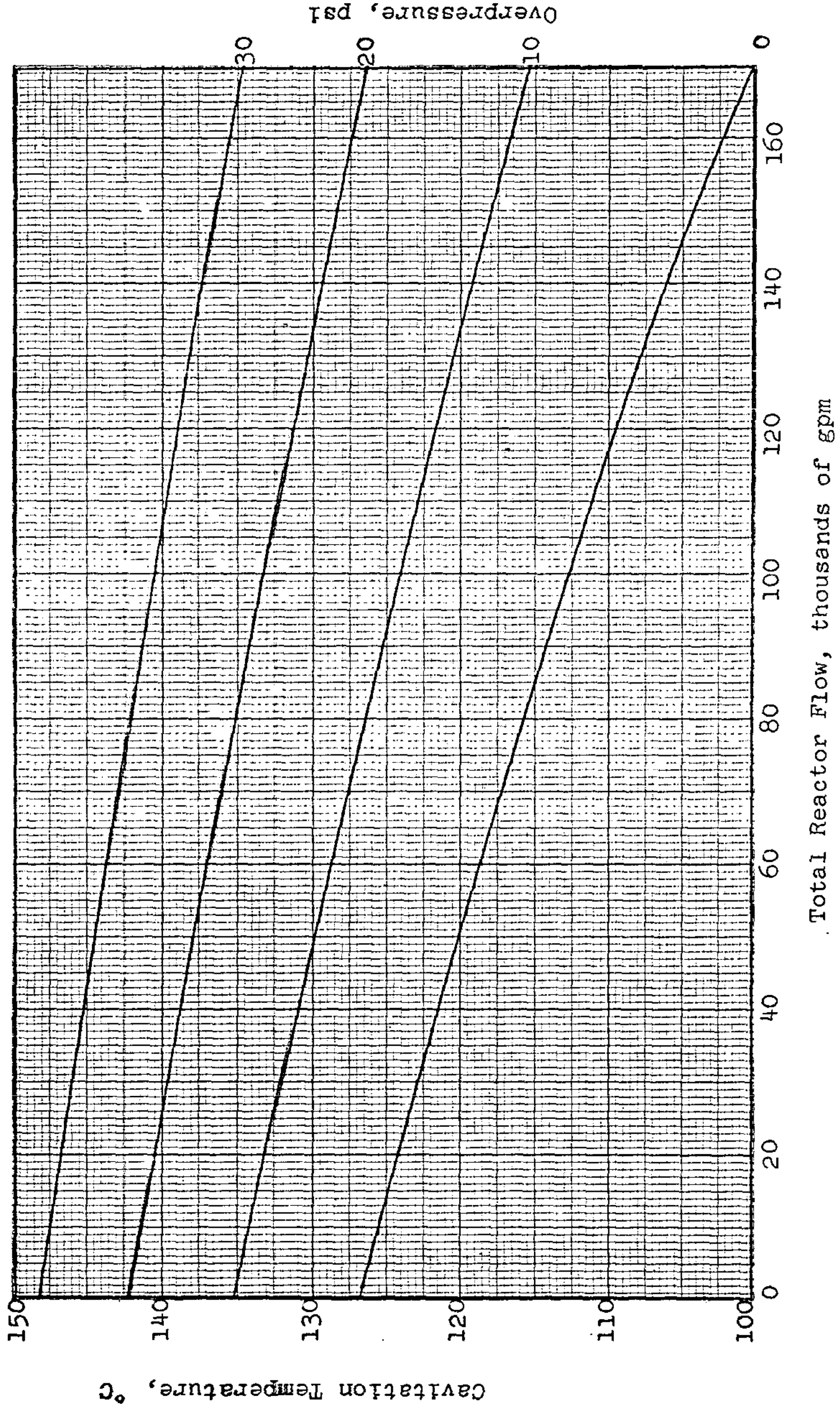


FIGURE 2

REACTOR CAVITATION CURVES IN TERMS OF SATURATION PRESSURE
(P-K Reactors)

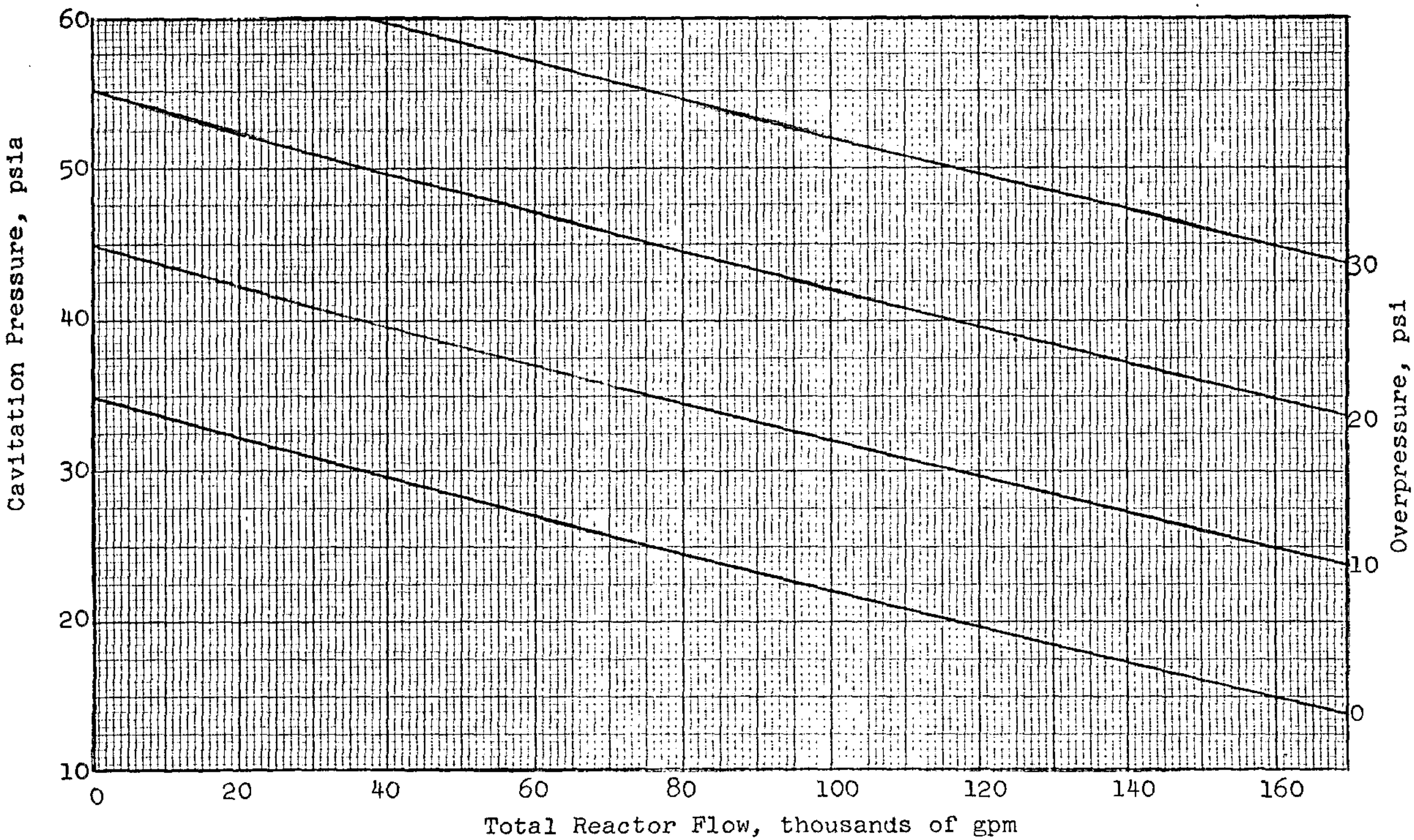
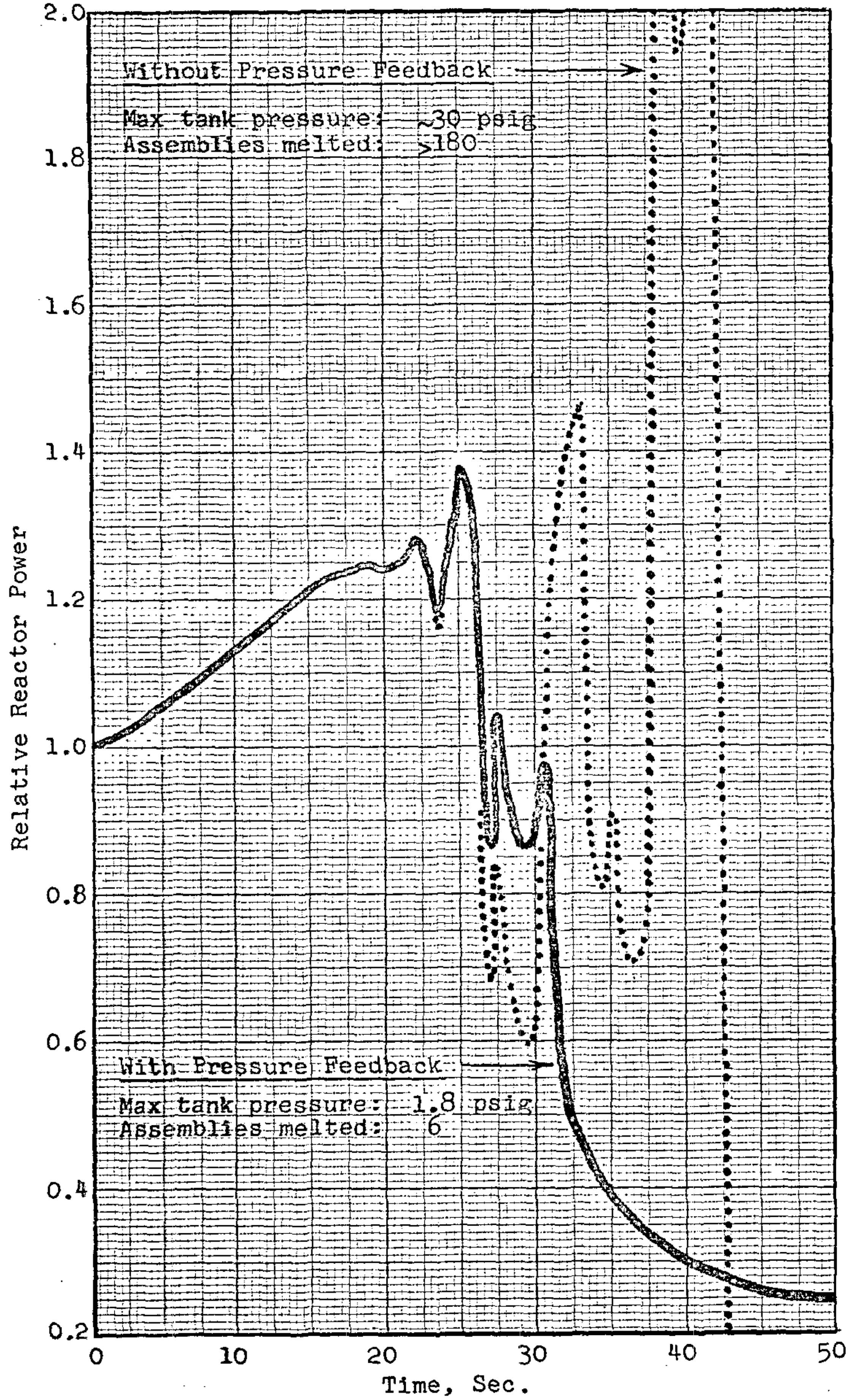


FIGURE 3

EFFECT OF PRESSURE FEEDBACK ON GANG ROD WITHDRAWAL ACCIDENT



APPENDIX

The equation for the calculation of overpressure in the reactor tank during a steam transient was derived by D. H. Knoebel based primarily on CMX steaming experiments. Beginning with the basic convection equation, the rate of heat transfer from the steam to the moderator is expressed as:

$$Q = h\ A\ \Delta T \tag{1}$$

where:

Q = rate of heat transfer, pcu/sec

h = heat transfer coefficient from the steam to the liquid, pcu/sec - ft^2 - °C

A = surface area for heat transfer, ft^2

ΔT = driving force, °C

The steam volume in the moderator space is assumed to take the form of a hemisphere on the tank bottom; hence the surface area for heat transfer becomes:

$$A = 2\pi r^2 \tag{2}$$

where:

A = surface area for heat transfer, ft^2

r = radius of the hemisphere, ft

The driving force is assumed to be the instantaneous moderator subcooling (SUBKUL), defined as the difference between the saturation temperature at the tank bottom (TLIM1) and the reactor effluent temperature (HPØ):

$$\text{SUBKUL}=\text{TLIM1}-\text{HPØ}=\Delta T \tag{3}$$

Thus:

$$Q = h(2\pi r^2)\text{SUBKUL} \tag{4}$$

An average heat transfer coefficient calculated from the Cross-flow Tank experiments was ~35 pcu/ft^2sec-°C. These experiments mocked up steaming from 36 assemblies in the reactor and increased pressure in the tank in the range of 2-7 psi. Coefficients of ~80 pcu/ft^2-sec-°C were calculated for experiments in the single lattice position tank which mocked up steaming from 600 assemblies; however, pressure increases were in the range of 40-95 psi with subcoolings in the range of 75-95°C. The lower value of the coefficient was selected because conditions in the Crossflow Tank more nearly matched those of accidents currently calculated by AA1.

Based on unpublished work of D. A. Ward, the overpressure in the reactor vessel caused by the resistance of the top shield to liquid water flow is:

$$\text{ØVERPR}=0.00305(\text{VØL})^{1.8} \quad (5)$$

where:

VØL = instantaneous unquenched steam volume in the tank, ft^3

If it is assumed that volume is a hemisphere, then:

$$\text{VØL}=2/3\ \pi r^3 \quad (6)$$

Rewriting equation (4):

$$r = (Q/2\pi h\text{SUBKUL})^{\frac{1}{2}} \quad (7)$$

Inserting equation (7) into equation (8)

$$\text{VØL}=2/3\ \pi(Q/2\pi h\text{SUBKUL})^{3/2} \quad (8)$$

inserting equation (8) into equation (5)

$$\text{ØVERPR}=0.00305\left[2/3\pi(Q/2\pi h\text{SUBKUL})^{3/2}\right]^{1.8} \quad (9)$$

Neglecting the heat capacity of the unquenched steam, Q may be expressed as the rate of steam injection into the tank during one calculational time increment by multiplying by the heat of vaporization and dividing by the duration of the calculational increment:

$$Q = \frac{\text{SF(INCRE)*475.}}{\text{DELTAT}} \quad (10)$$

Collecting constants and inserting equation (10) into equation (9):

ØVERPR=0.00305*(2.094*(SF(INCRE)*2.16/(SUBKUL*DELTAT))**1.5)**1.8